R. P. NOTE 93

CHARACTERISTICS OF NEUTRON RADIATION FIELDS OUTSIDE OF SHIELDING

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Introduction

Cossairt, et al.[1] have summarized measurements of neutron spectra at various locations within tunnels and outside the shielding at a high-energy accelerator complex at Fermilab. Since then, over the last three years, other measurements have been performed. We summarize the results of all measurements done at Fermilab at locations outside the shielding. Such data is useful to both the determination and evaluation of personnel dosimetry for radiation workers at a high-energy accelerator laboratory.

Technique

All the measurements were performed by use of a multisphere spectrometer, the technique originally suggested by Bramblett, et al.[2] The spectrometer consisted of either ^{6}LiI scintillators or ^{6,7}Li TLDs placed at the center of moderating spheres with diameters ranging from 5.08 to 45.7 cm, and a bare, unmoderated, detector. The detection of thermal neutrons after moderation was based on the ^{6}Li (n,α) ^{3}H thermal neutron capture reaction. The raw data for a measurement are the relative responses for the set of spheres in the radiation field.

The experimental technique and the subsequent conversion of the raw data into neutron spectra by the use of unfolding methods has been discussed in a number of reports,[3] and is not repeated here. We also do not discuss the well-known difficulties inherent in the spectrum unfolding problem due to its underdetermined and ill conditioned nature. Suffice to say that a number of independent unfolding programs have been utilized in all of the measurements in order to gain some confidence in the results. In most cases, the different programs result in low resolution spectra which agree with each other in macroscopic features but not always in specific details. Integral properties, however, such as average quality factor, total fluence, and total dose equivalent are essentially independent of the choice of unfolding program. It is these quantities that we summarize in this report.

We note furthermore, as pointed out by a number of authors,[4] that response functions for the largest sphere are not well-known above 25 or 50 MeV, and other techniques should be used to better quantify the high-energy contribution. Thus, there may be some uncertainty in the fluence and dose equivalent at the highest energy range reported here.

Results

Examples of some of the neutron energy spectra whose properties are summarized in this report are given in Ref. 1, which is included as an Appendix. Table 1 in the present report lists the fraction of total neutron fluence and dose equivalent for five energy ranges, along with the Quality Factor of the neutron radiation field. The last column in the Table lists the averages of the results for the fourteen spectra. The locations for the spectral measurements are representative of the areas in which persons might be present during a typical Fermilab experimental running period. It should be noted that dose equivalent rates at all locations were in compliance with the requirements outlined in the Fermilab Radiation Guide[5] during the periods of measurement.

Conclusion

We draw the following conclusions from Table 1:

1. Although 77% of neutron fluence arises from neutrons with energy below 0.1 MeV, only 23% of the total dose equivalent is from neutrons at these energies.

2. About 77% of the dose equivalent arises from neutrons with energies greater than 0.1 MeV, and nearly 50% of the dose equivalent from those with energies greater than 2 MeV. Note that only about 13% of the fluence is above this latter energy.

3. The average value of the Quality Factor is 5.3, equivalent to the value of 5 that has traditionally been accepted as the Fermilab average Quality Factor, and is the "neutron setting" on the Chipmunk radiation monitors.

Currently, at Fermilab, Lexan polycarbonate track detectors are used for neutron dosimetry. These materials have a threshold at about 1 MeV and an upper limit that is not well-known but at least registers a reasonable response at about 20 MeV. CR-39 track-etch detectors may be more attractive for the Fermilab environment because of a threshold of 0.1-0.2 MeV. However, the response at ~20 MeV, while not well-known, is down by factors of 5-10 from its peak value at about 2 MeV. While NTA film has excellent fast neutron sensitivity with a threshold at 0.5 to 0.7 MeV, latent image fading is a major problem, and the film is also sensitive to gamma rays and x-rays. TLD albedo dosimeters, on the other hand, are relatively insensitive to just those neutrons which contribute to most of the Fermilab dose equivalent. While a number of laboratories have experienced limited success with such dosimeters, the generally poor response to accelerator-generated neutrons ensure that track-etch detectors (Lexan, CR-39 plastic) or nuclear emulsions (NTA film) remains the method of choice for the individual monitoring of neutrons at high-energy accelerator laboratories.

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TABLE 1

PERCENT FLUENCE AND DOSE EQUIVALENT OUTSIDE SHIELDING

	A	B	C	D	E	F	G	H	I	J
1		BIN RANGE	SPECTRUM 1	SPECTRUM 2	SPECTRUM 3	SPECTRUM 4	SPECTRUM 5	SPECTRUM 6	SPECTRUM 7	
2										
3	FLUENCE	<1.5 eV	31.5	42	24	29	23.3	40.4	35	
4		.0015-100 keV	12.5	4.5	45.9	39	45	52.3	58.2	
5		.1-2 MeV	8.5	1	12.2	19.5	10.7	0.4	6.7	
6		2-25 MeV	40.5	2.5	17.6	10	21	6.9	0	
7		>25 MeV	7	50	0.3	2.5	0	0	0	
8										
9	DOSE EQUIVALENT	<1.5 eV	1.5	2	2.3	3	2.1	11.6	16.7	
10		.0015-100 keV	0.5	0.2	6.3	6	5.4	15.8	29.6	
11		.1-2 MeV	9	0.4	11.1	41	23	2.2	53.6	
12		2-25 MeV	75	4	79.4	38	69.5	70.4	0.1	
13		>25 MeV	14	93.5	1	12	0	0	0	
14										
15	QUALITY FACTOR		5.8	4.2	5.9	6.2	7.4	7.5	3.7	
16										
17		BIN RANGE	SPECTRUM 8	SPECTRUM 9	SPECTRUM 10	SPECTRUM 11	SPECTRUM 12	SPECTRUM 13	SPECTRUM 14	AVERAGES
18										
19	FLUENCE	<1.5 eV	34.8	28	55	29.7	35.7	33.5	33.5	34.0
20		.0015-100 keV	58.1	46	43	41.7	51.9	62.1	48	43.4
21		.1-2 MeV	7.4	17.5	2	26.4	7.7	0	18.4	9.9
22		2-25 MeV	0	4.5	0.1	2.2	4.8	2.1	0.4	8.0
23		>25 MeV	0	4	0	0	0	2.3	0	4.7
24										
25	DOSE EQUIVALENT	<1.5 eV	16.5	4	41.5	4.1	8.3	12.5	7.5	9.5
26		.0015-100 keV	30.8	11.5	37	6.2	12.2	22.3	10.9	13.9
27		.1-2 MeV	52.7	35	17	79.1	41	0.1	81.3	31.9
28		2-25 MeV	0	24	3.5	10.6	38.4	28	0.3	31.5
29		>25 MeV	0	25	1	0	0	37.1	0	13.1
30										
31	QUALITY FACTOR		3.8	5.4	2.5	7.4	5.5	3.4	6	5.3
32										
33	SPECTRUM 1	Debuncher Ring at AP10			SPECTRUM 8	Roof 4 over PC4				
34	SPECTRUM 2	Debuncher Ring at AP30			SPECTRUM 9	ME Target Magnet, No Concrete				
35	SPECTRUM 3	Vault above LI Lens at AP0			SPECTRUM 10	ME Target Magnet, Concrete Added				
36	SPECTRUM 4	PC Hyperon Extension Roof, DS(1)			SPECTRUM 11	ME Electronics Room, Access Door				
37	SPECTRUM 5	PC Hyperon Extension Roof, DS(2)			SPECTRUM 12	MC Beam, at ME Electronics Room, Access Door				
38	SPECTRUM 6	PC Hyperon Extension Roof, US			SPECTRUM 13	MC, Catwalk above Target Pile				
39	SPECTRUM 7	Roof 1 over PC4			SPECTRUM 14	MW, Catwalk above Target Pile				

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Measurements of Neutrons in Enclosures and Outside of Shielding at the TEVATRON*

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ABSTRACT

The characteristics of the spectra of neutrons produced by the losses of accelerated proton beams both within accelerator enclosures and outside of shielding has been determined from measurements at various locations around the Fermilab Tevatron and its associated experimental areas. The measurements were performed with a multisphere spectrometer consisting of either ^{6}LiI scintillators or ^{6,7}LiF TLD's placed at the centers of moderating polyethylene spheres with diameters ranging from 5.08 to 45.7 cm. The fluence and dose equivalent energy distributions and average quality factors obtained from spectrum unfolding calculations are summarized for this accelerator environment. (Fermilab is operated by Universities Research Association under contract with the U. S. Department of Energy.)

1. INTRODUCTION

In health physics evaluations at high energy accelerators, the complex nature of the radiation requires that one properly characterize it in order to determine parameters important for operational health physics concerns. Often, the fields encountered are dominated by neutrons. Therefore, a measurement of the neutron energy spectrum is useful to obtain a complete understanding of them. In special cases this spectral information is also needed by accelerator physicists who are attempting to predict possible radiation damage to equipment, particularly to electronic components. This paper summarizes measurements of such energy spectra at Fermilab using the familiar multisphere method. A brief description is given of the experimental technique and the unfolding methods used. Examples are drawn from measurements, both within accelerator enclosures and external to a number of different shielding materials and configurations, conducted by a number of people over the last several years. Finally, several checks of the validity of the experimental technique are presented.

2. EXPERIMENTAL TECHNIQUE

The familiar multisphere technique was initially suggested by Bramblett, et. al. (1) and more recently summarized by Awschalom and Sanna (2). In nine measurements described here, neutrons were moderated by a set of polyethylene spheres containing a thermal neutron detector and having a range of diameters [5.08, 7.62, 12.7, 20.4, 25.4, 30.4, and (for some measurements) 45.7 cm]. A datum without moderation (bare detector) was always taken as well. The detection of thermal neutrons after moderation by the spheres was based on the exothermic ^{6}Li(n,α)^{3}H thermal capture reaction (Q-value = 4.78 MeV, $\sigma_{n,\alpha}$ = 940 barns). The raw data for a measurement are the relative responses for the set of spheres in the radiation field.

For one of the measurements, accessibility and high dose rate considerations dictated the use of ^{6}LiF/^{7}LiF thermoluminescent dosimeters. Standard TLD calibration and readout techniques were used. In this instance, the responses of the ^{7}LiF TLD's were necessary in order to account for a background due to photons and charged particles. The other measurements used LiI(Eu) scintillators, enriched to 99% ^{6}Li. For seven of these, a small ^{6}LiI(Eu) crystal (8 mm diameter by 8 mm long) was embedded in a cylinder of plastic scintillator (12.7 mm diameter by 12.7 mm long). The light output from both was viewed by a single photomultiplier tube. This "phoswich" detector has been described previously by Awschalom and Coulson (3). Fast pulses (2-3 nsec) from the plastic scintillator were separated from the relatively slow (1-2 msec) pulses from the ^{6}LiI(Eu) by passive filters at the phototube output. Standard modular electronics were used to accumulate a pulse height spectrum in a multichannel analyzer of all slow pulses in anti-coincidence with fast signals. This method rejects events due to the passage of charged particles (such as muons) through the ^{6}LiI(Eu), thus reducing the background underneath the (n,α) peak in the pulse height spectrum. Signals synchronized to the accelerator cycle were used to gate the detectors on only during the ≈ 20 s duration of the beam spills, which occurred approximately once per minute.

In general the sphere responses were measured one at a time because of concerns about nonuniformities in the radiation field and sphere-to-sphere "crosstalk". Normalization was provided by the use of either tissue equivalent ion chambers or relevant beamline instrumentation (ion chambers or secondary emission intensity monitors). In one measurement, data were taken simultaneously with an array of eight ^{6}LiI(Eu) (12.7 mm diameter by 12.7 mm long) crystals. In this case simple pulse height spectra with appropriate selection of the (n,α) peak sufficed to define events due to thermal capture. In fact, for all eight measurements with ^{6}LiI(Eu), the (n,α) peak was very cleanly resolved.

Conversion of the raw response data into a neutron spectrum involves the multisphere unfolding problem. This has been discussed by many authors and we only summarize briefly here. The counting rate C_r of a thermal neutron detector at the center of a spherical moderator of radius r is given by

$$C_r = \int_0^\infty \frac{dN}{dE} R_r(E) dE \ ,$$

where dN/dE is the differential flux density of neutrons incident on the moderator and $R_r(E)$ is the energy-dependent response function for the sphere of radius r. Given C_r and $R_r(E)$, the problem is to find dN/dE. In practice, one uses a discrete approximation to the above,

$$C_r = \sum_i \frac{dN}{dE_i} R_r(E_i) \Delta E_i \ ,$$

where dN/dE_i is the differential neutron flux for the ith energy group. The response functions $R_r(E_i)$ are obtained in separate calculations and have been tabulated by a number of workers. For this work, those of Sanna (4), appropriate for our scintillator dimensions and moderator densities (0.92 g cm^{-3}), were chosen. Recently, measurements of similar response functions have been reported by Kosako, Nakamura, and Iwai using a time-of-flight technique (5). The values of C_r are the set of appropriately normalized measured detector responses.

As is well known, the spectrum unfolding problem has inherent difficulties due to its underdetermined and ill-conditioned nature (6). In order to gain some confidence in the results, three different programs were used during the course of this work. These were BUNKI (7,8), LOUHI (9), and SWIFT (10). The latter is based upon Monte-Carlo techniques without *à priori* assumptions as to the character of the spectrum. It was used as a check on the other two which are based, respectively, on an iterative recursion method and a least-squares method with user-controlled constraints. For this work, the initial spectrum was usually chosen to have a 1/E dependence. The results using SWIFT confirmed the viability of this choice. All three programs result in low resolution spectra which agree with each other in macroscopic features but not always in specific details at individual energy bins. Integral properties such as average quality factor, total fluence, total absorbed dose, and total dose equivalent are, however, essentially independent of the choice of unfolding program used.

3. MEASURED SPECTRA

Figures 1, 2, and 3 show the geometry involved in each of the nine measurements (left side) and a plot of the corresponding neutron energy spectrum determined using the unfolding program BUNKI (right side). Each spectrum is denoted by a capital letter and is plotted as flux per unit *logarithmic* energy interval. This type of plot was suggested by Rohrig (11) and results in the area under the curves for each energy bin being proportional to the neutron fluence within that bin. The usually dominate 1/E dependence is suppressed in such a plot.

Spectrum A arose from 8 GeV protons being targeted on a magnet in the Debuncher storage ring (normally used to store antiprotons for the Fermilab colliding beams program). The spheres were located external to a 671 g cm^{-2} shield of earth and concrete.

Spectrum B resulted from 8 GeV protons being targeted on a magnet in a different part of the same Debuncher storage ring. Here spheres were located external to a 402 g cm^{-2} thick shield of earth and concrete plus some iron just below the spheres.

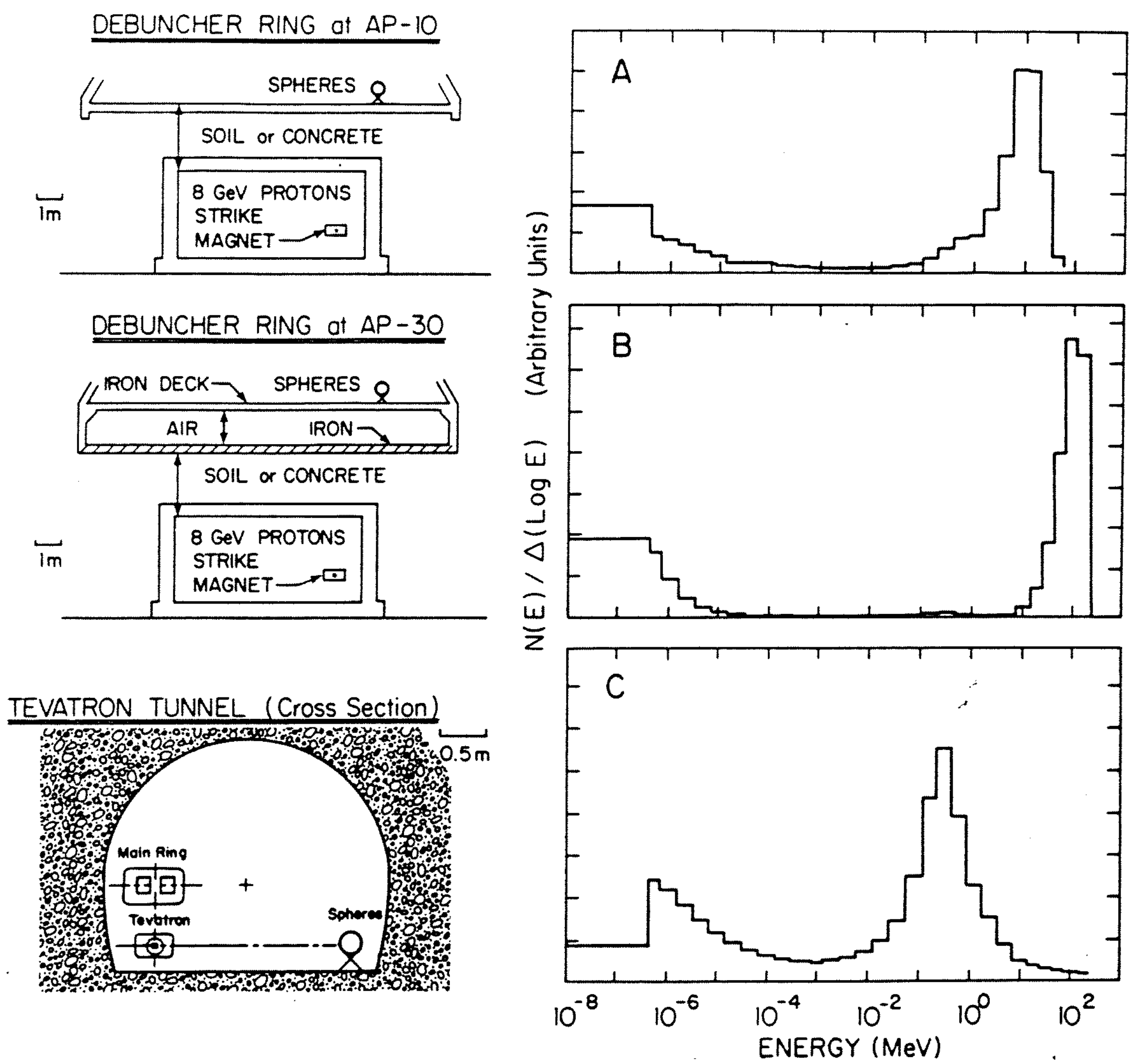


Figure 1. Shielding geometries (left) and corresponding unfolded neutron energy spectra (right) for situations A, B, and C. The abscissa is in arbitrary units of fluence per logarithmic energy interval.

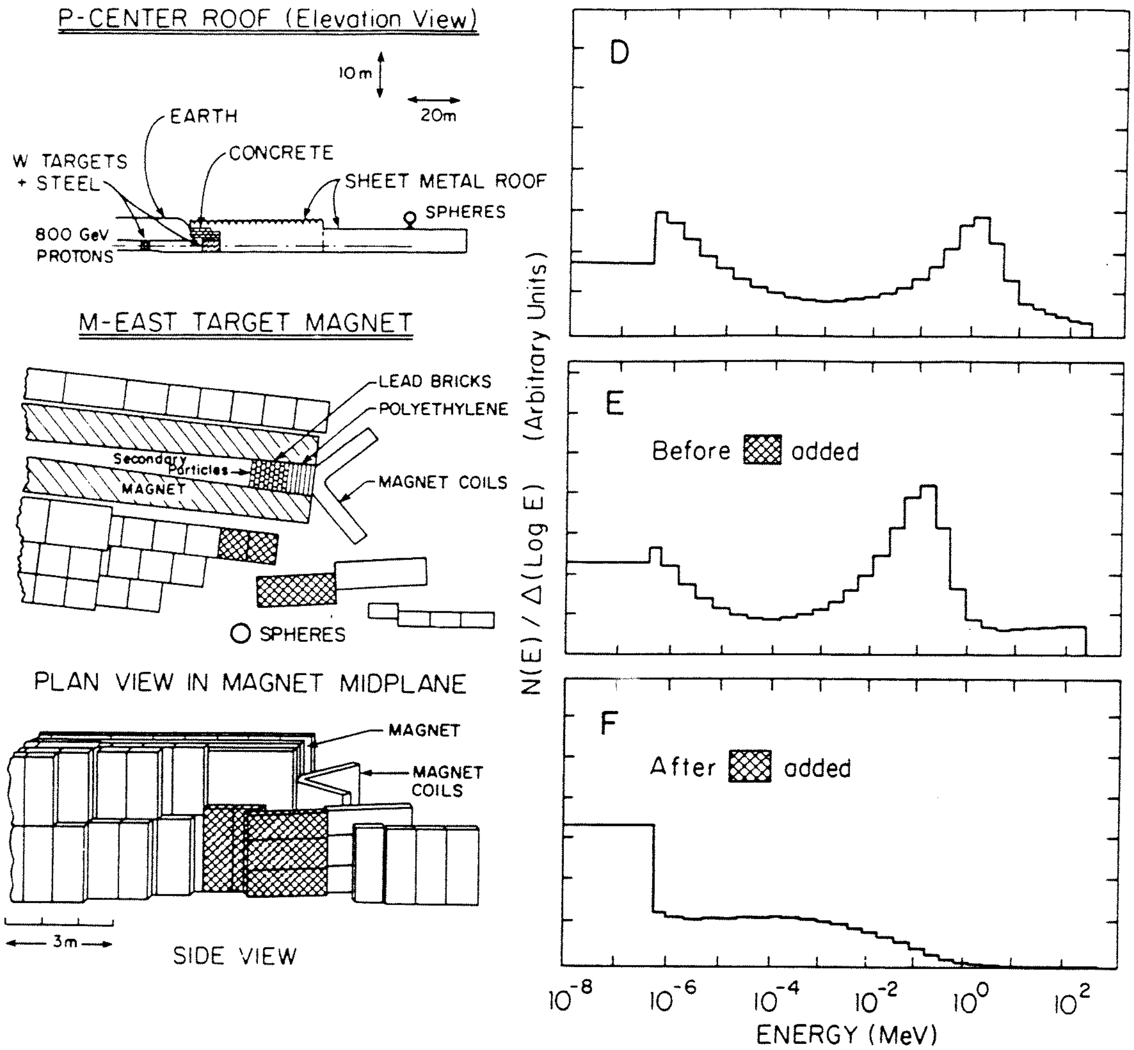


Figure 2. Shielding geometries (left) and corresponding unfolded neutron energy spectra (right) for situations D, E, and F. The abscissa is in arbitrary units of fluence per logarithmic energy interval.

Spectrum C was obtained in the Tevatron tunnel with the spheres located on the wall opposite to the accelerator elements. Data was collected using the array of 8 detectors supplied and operated primarily by personnel from the Lawrence Berkeley Laboratory. Neutrons were produced from 800 GeV protons interacting with residual gas in the Tevatron vacuum chamber during circulating beam conditions. Details are given by Freeman, et. al. (12).

Spectrum D was obtained relatively far downstream of a large target and beam dump system struck by 800 GeV protons and shielded by iron and concrete. It is described in detail by Cossairt and Elwyn (13).

Spectra E and F were obtained laterally to a large electromagnet which contained a beam dump within its gap. This beam dump was struck by 800 GeV protons. For E the spheres viewed the bare iron return yoke of the magnet while for F this return yoke was mostly covered with additional concrete shielding as shown. Details are given by Elwyn and Cossairt (14).

Spectrum G was obtained on top of the downstream end of a beam dump and target assembly involving 800 GeV protons incident on a target followed by bending magnets and a beam dump. The entire assembly was shielded by an inner layer of iron and an outer layer of concrete in the

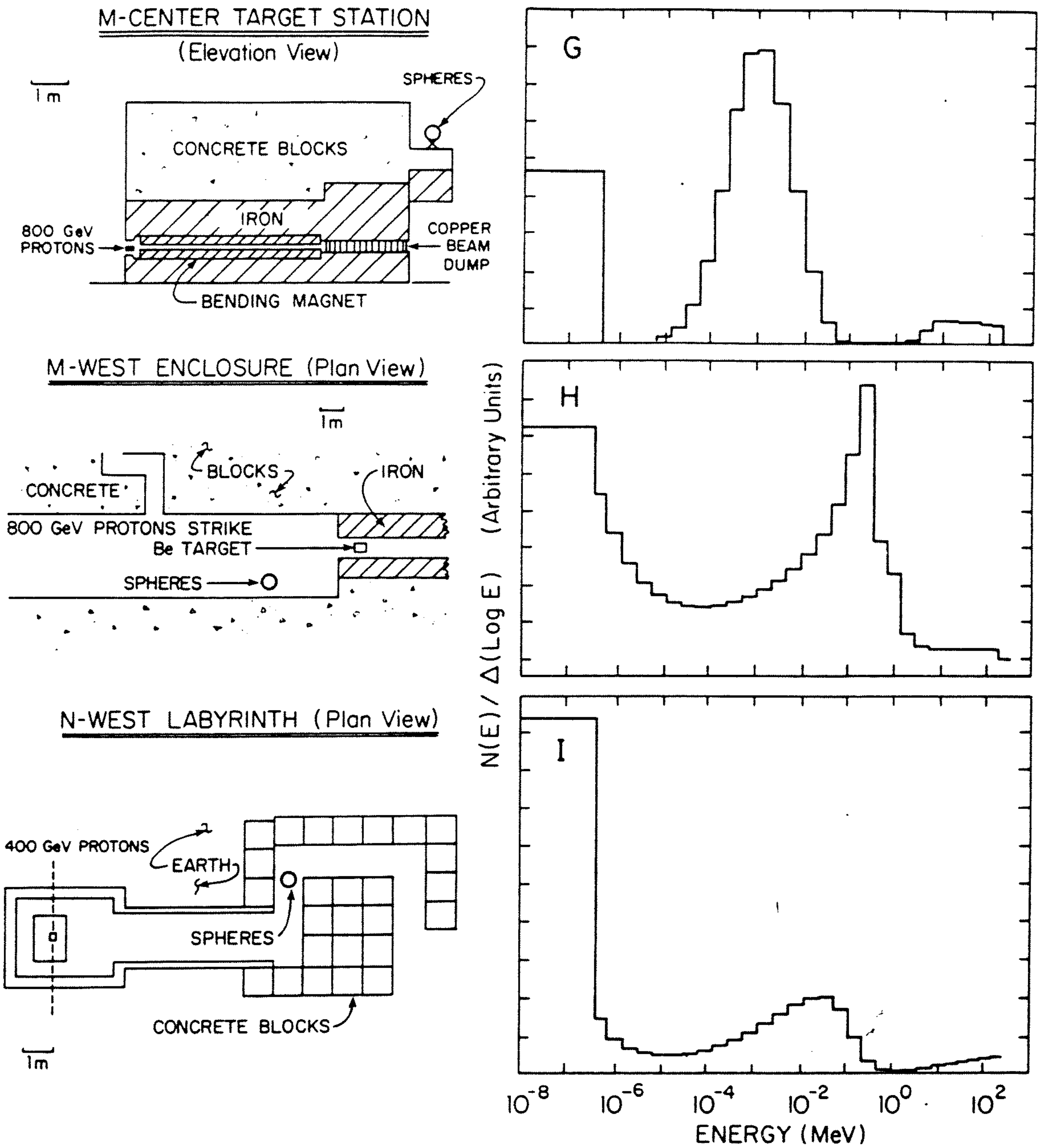


Figure 3. Shielding geometries (left) and corresponding unfolded neutron energy spectra (right) for situations G, H, and I. The abscissa is in arbitrary units of fluence per logarithmic energy interval.

form of large blocks.

Spectrum H was obtained in a beam enclosure in which 800 Gev protons struck a target in an iron cave. It is the average of two sets of measurements. The detectors thus viewed "backscatter" from this target. This is the single instance in which TLD's were used.

Spectrum I was obtained in the second "leg" of a labyrinth. The neutrons were produced by 400 GeV protons striking an aluminum target inside a large pipe beneath the floor of the main enclosure. For details see Cossairt, et. al. (15).

The properties of the various neutron spectra are compared in Tables 1 and 2 where the relative fluence and dose

Table 1. Percent Fluence in Specific Energy Bins for Unfolded Neutron Spectra

Spectrum-> Energy	A	B	C	D	E	F	G	H	I
< 1.5 eV	31.5	42	19.5	29	28	55	33.5	42	71
0.0015-100 keV	12.5	4.5	36	39	46	43	62.1	36.2	24
0.1-2 MeV	8.5	1	36	19.5	17.5	2	0	19.4	2
2-25 MeV	40.5	2.5	7	10	4.5	0.1	2.1	1.5	1
> 25 MeV	7	50	1.5	2.5	4	0	2.3	0.9	1.5

Table 2. Percent of Dose Equivalent in Specific Energy Bins for Unfolded Neutron Spectra Along with Average Quality Factors

Spectrum-> Energy	A	B	C	D	E	F	G	H	I
< 1.5 eV	1.5	2	2	3	4	41.5	12.5	9	32
0.0015-100 keV	0.5	0.2	6	6	11.5	37	22.3	11.9	16
0.1-2 MeV	9	0.4	58.5	41	35	17	0.1	59.8	9
2-25 MeV	75	4	26	38	24	3.5	28	11.5	13
> 25 MeV	14	93.5	7.5	12	25	1	37.1	7.9	30
Average Q.F.	5.8	4.2	6.9	6.2	5.4	2.5	3.4	5.7	3.1

equivalent in rather broad energy bands is tabulated. Table 2 also lists average quality factors from the unfolded spectra. Some points of interest follow:

Several of the spectra show fluence peaks between ≤ 0.1 and a few MeV (e.g. C, D, E, and H). All of these involve iron shields or magnets around or near to the neutron source, and the observed peak represents those neutrons that "leak" through the material because of its small nuclear inelastic cross sections at these energies (16). Spectrum F represents a dramatic illustration of how augmenting the iron shield with concrete removes these neutrons almost completely (14).

Spectra A and B show sizeable contributions from neutrons with energies > 2 MeV (up to ≈ 100 MeV). The geometry in these cases consists of relatively thick concrete shields that allow the buildup of high-energy cascade particles. Greater than 50 % of the fluence and 90 % or more of the dose equivalent arises from the very high-energy neutrons. The peak at around 1 keV in spectrum G may be due to neutrons leaking through the many cracks surrounding the concrete blocks.

Thermal neutrons contribute importantly to the observed spectra in almost all cases since the measurement locations were within concrete tunnels and enclosures, or in the vicinity of large concrete block shields. Even so, most of the dose equivalent arises from higher energy neutrons. For example, for spectrum I (within a concrete block labyrinth) 71 % of the fluence but only ≈ 30 % of the dose equivalent is contributed by thermal neutrons. In general, then, neutrons with energies of a few MeV or greater are the major health physics concern in this accelerator environment. The average quality factor of the nine spectra is 4.8 ± 1.6, in good agreement with results obtained by others, for example Patterson, Routti, and Thomas (17), for similar spectra outside of accelerator shielding.

4. VERIFICATIONS

Given the nature of the spectrum unfolding problem, it is important to verify that the unfolded spectra are reasonable. First, one can look at how the behavior of the raw data, C_T, as a function of sphere size compares with the fact that the calculated responses, $R_T(E)$, peak at energies that increase monotonically with radius. Figure 4 shows measured sphere responses as a function of sphere diameter for spectra E and F (top) and I (bottom) superimposed on the best fits to these data that result from the unfolding calculation. For spectra E and F, it is quite clear that the raw data reflect the effective removal of the "iron leakage peak" by the added concrete. For spectrum I, it is clear that though the spectrum has a large contribution from low energy neutrons, the sphere responses differ significantly from those expected from a pure thermal spectra, thus enhancing one's confidence in the existence of a peak at a somewhat higher energy. Figure 5 is an additional verification of this type for spectrum C using the LOUHI unfolding program (which produced results similar to those obtained using BUNKI shown in Fig. 1). In this figure, the measured responses (open circles) and the best fit by the unfolding calculation (solid curve) are compared to results expected if all of the fluence were concentrated in the specified energy bins.

A second verification is a measurement of the spectrum of a ^{238}Pu-Be source. The measurements were performed in the Fermilab "calibration" room, the upstrairs of a brick farm house, by measuring the sphere responses at varying distances from the source in order to correct for room-scattering contributions following Eisenhauer, et.al. (18). The derived correction factor was, as expected, most important for the smaller spheres. Figure 6 shows the detector responses, both total and corrected for room scattering, along with the corresponding spectra unfolded with BUNKI. Except for fewer thermal neutrons in the corrected spectrum good agreement with a multisphere spectrum reported by Thorngate and Griffith (19) was obtained.

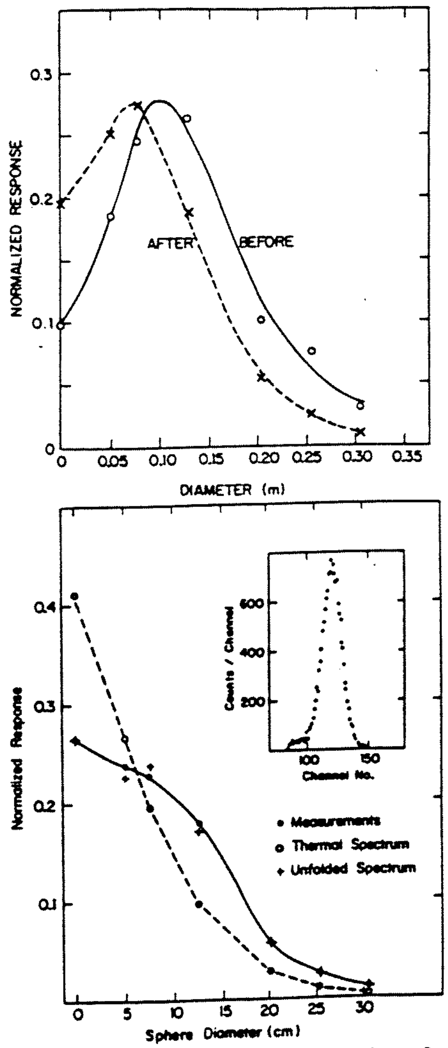


Figure 4. Detector response as a function of sphere diameter for situations E ("before") and F ("after") [top] and I [bottom]. In the top frame the curves are calculated from the unfolded spectrum while the symbols are the measurements. The curves in the bottom frame are drawn to guide the eye. The bottom frame also shows a typical pulse height spectrum of the (n,α) peak obtained using the "phoswich" detector.

Third, one can compare average quality factors inferred by use of the unfolding programs with those obtained independently using a technique based upon measurements of columnar recombination developed by Sullivan and Baarli (20) and described in some detail for our application in Ref. 15. Such comparisons have been done for several of the spectra presented here with the results summarized in Table 3. Agreement within the experimental errors is found.

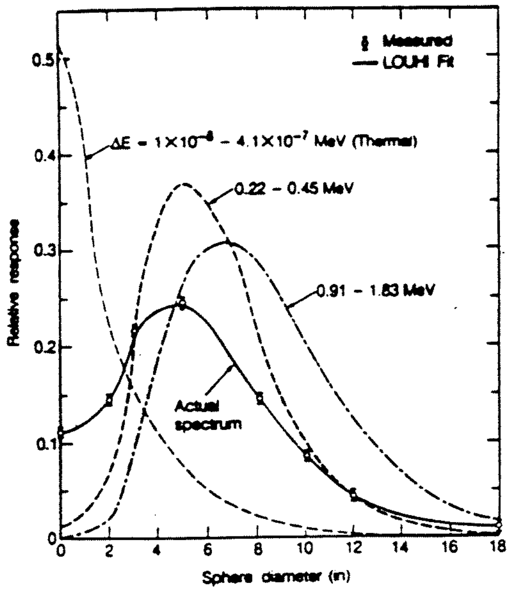
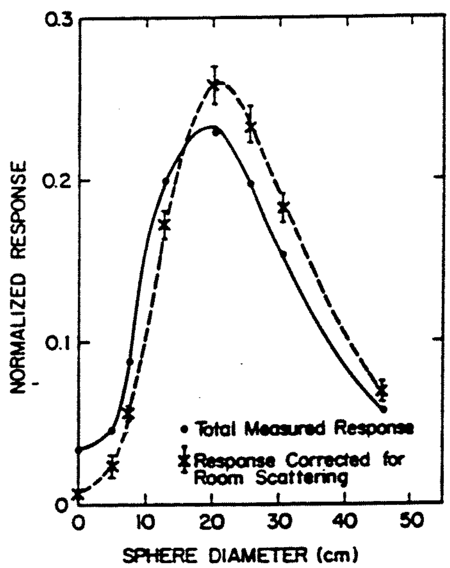


Figure 5. Detector response as a function of sphere diamter for situation C both as measured (data points) and as unfolded (solid line) using LOUHI compared with results expected for "pure" population of the indicated energy domains.

Table 3 Average Quality Factors

Spectrum	Technique	
	Unfolding	Recombination
D	1.4 ± 0.2*	1.1 ± 0.3 *
E	5.4 ± 0.2	6.0 ± 0.6
F	2.5 ± 0.3	3.0 ± 0.3
I	3.1 ± 0.7	3.4 ± 0.1

*Mixed field, includes muon component



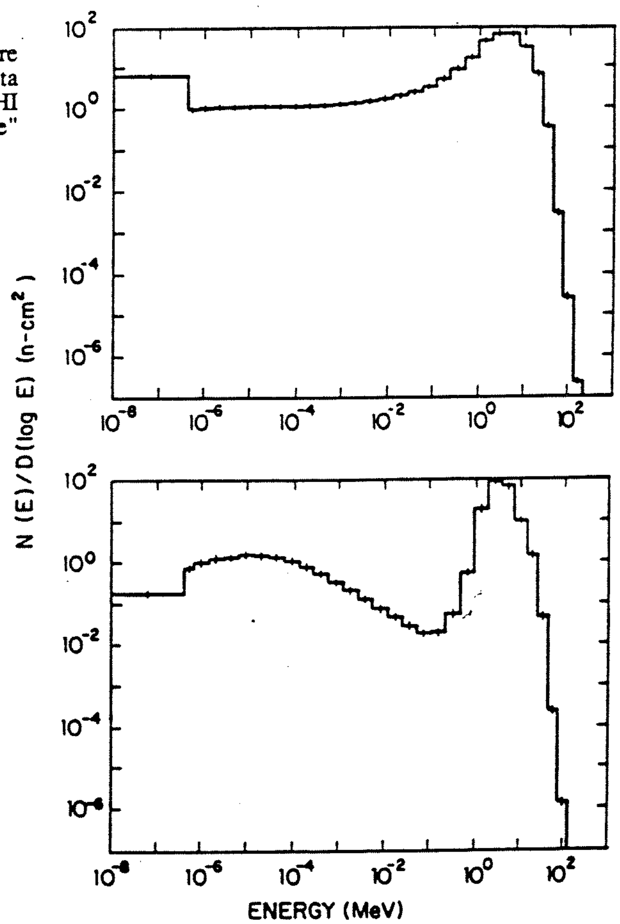


Figure 6. Detector response as a function of sphere diameter both uncorrected (top right) and corrected (bottom right) for room-scattering in the field of a ^{238}Pu-Be source (left) and resultant unfolded spectra using BUNKI.

Unfolded neutron energy spectra should be explained by reasonable theory. Figure 7 compares a calculation by O'Brien (21) for a 500 g cm^{-2} thick iron shield around a generic high energy accelerator with the shape of the BUNKI result for spectrum E. The agreement for the domain $0.001 < E < 1$ MeV is excellent, given the fact that the low resolution multisphere technique should not reproduce all of the structure within the calculated "leakage" peak. An enhancement of thermal neutrons in spectra E and F, which arises from the location within a concrete enclosure, should not be predicted in the calculation. A calculation for a 1000 g cm^{-2} pure earth shield is also given in Ref. 21. This spectrum, superimposed for example on spectrum B, is shown in Fig. 7 and is dominated by two prominant peaks at the high energy end. While none of the spectra discussed here involve only earth shielding, several of the spectra (A, B, D, G, and I) do exhibit some peaking in the same energy region. Similar peaks have been seen in other studies, for example the famed CERN-LRL-RHEL experiment (22).

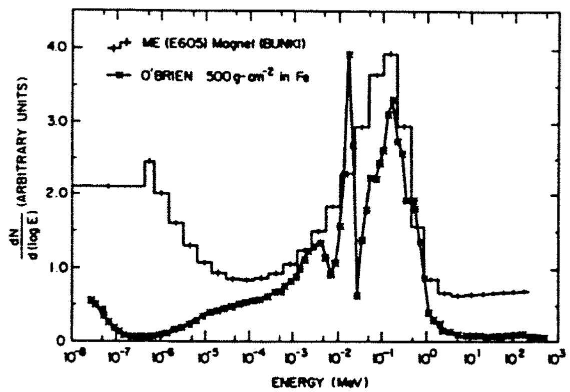


Figure 7. Unfolded spectrum from situation E using BUNKI superimposed on the calculation of O'Brien for an iron shield (Ref.21).

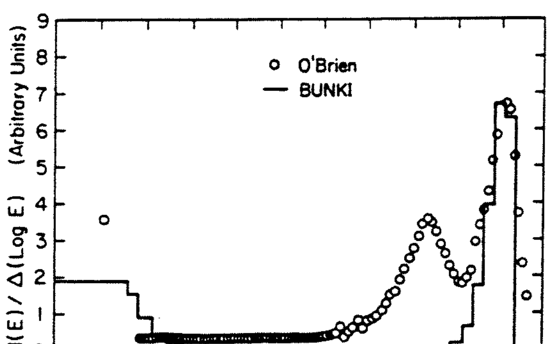


Figure 8. Unfolded spectrum from situation B using BUNKI superimposed on the calculation of O'Brien for a concrete shield (Ref.21).

5. CONCLUSION

The multisphere technique, in spite of inherent difficulties, can lead to reliable estimates of low resolution neutron energy spectra in the various radiation fields encountered at Fermilab. This technique is useful for detailed environmental and occupational dose equivalent assessments and in guiding design of accelerator shielding.

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